

# Three-dimensional Motor Schema Based Navigation

Ronald C. Arkin  
School of Information and Computer Science  
Georgia Institute of Technology  
Atlanta, GA 30332

## Abstract

Reactive schema-based navigation is possible in space domains by extending the methods developed for ground-based navigation found within the Autonomous Robot Architecture (AuRA). Reformulation of two dimensional motor schemas for three dimensional applications is a straightforward process. The manifold advantages of schema-based control persist, including modular development, amenability to distributed processing, and responsiveness to environmental sensing. Simulation results show the feasibility of this methodology for space docking operations in a cluttered workarea.

## 1. Introduction

One of the most important aspects of intelligent robotic control, whether teleoperated or otherwise, is a tight coupling between sensor data and motor action. It is crucial for the successful real-time operation of a robotic system that incoming perceptions be used as rapidly as possible. This strategy typically precludes the building of dynamic world models to reason over. Reflexive navigation provides highly reactive robotic control systems at a level beneath high-level planning and reasoning.

Space applications for reactive control require reformulation of the techniques developed for ground-based navigation. On earth, mobile robots typically have three controllable degrees of freedom: two for translation and one for rotation. In the micro-gravity environments of space, six degrees of freedom are present: three of translation and three of rotation (roll, pitch, and yaw). Navigation is both simplified and complicated by this change; simplified in the sense that there are more ways too move about in the world, complicated by the increased search space for solutions and the increased complexity of control.

Our previous work in ground-based navigation, conducted within the context of the Autonomous Robot Architecture (AuRA), can be readily extended into three dimensional problem domains. This includes both aerospace and undersea environments. One of the design goals of AuRA was to ensure domain independence as much as possible. This was accomplished through the use of modular design for perceptual strategies and motor behaviors, sensor and vehicle independence, and techniques for knowledge representation that are easily generalized. We have successfully demonstrated navigation of a ground-based

mobile robot in the interior of buildings [2], the outdoors of a college campus [6], and in manufacturing settings [3].

This paper illustrates how the reactive/reflexive component of the AuRA architecture can be extended into three dimensional worlds. Other researchers have addressed reactive navigation for ground-based applications. Brooks' subsumption architecture [7], Payton's reflexive behaviors [12], Kadonoff's [8] arbitration techniques are several examples of this navigational paradigm. Our work in motor-schema based navigation [1] also fits into this category. It is a straightforward extension of our behavioral methodology into this new domain.

We first review two-dimensional schema-based navigation in order to provide a firm basis for its extension into three dimensional worlds. The next section describes the modifications made to the motor schemas to produce 3D navigation. Simulations are then presented showing the ability of the robot to navigate in a cluttered world and successfully dock with a workstation. Finally, a summary, conclusions, and discussion of future work completes the paper.

## 2. Review of 2D schema-based navigation

Schema-based navigation [1] involves the decomposition of motor tasks into a collection of primitive behaviors called motor schemas. Each of these schemas produces an individual velocity vector using an analog of the potential field methodology [9,10,11]. The vector output of each of these individual motor schemas is summed and transmitted to the robot. This overall vector constitutes the desired speed and direction of the robot.

Embedded within each of the motor schemas is one or more perceptual schemas that provide the necessary information for a particular robot behavior. We have used video cameras [6], shaft encoders, and ultrasonic sensors [2] as input sensor devices for the perceptual schemas. Action-oriented perception is the basis for sensor interpretation. Only the information that is required for a particular motor activity is extracted from the incoming data. This makes computational processing tractable. The use of a divide-and-conquer strategy for partitioning sensor algorithms based on motor needs, focus-of-attention mechanisms, and the application of expectation-based perception (both from *a priori* environmental knowledge and previous sensor data) facilitate rapid response. We have previously described the relationship of this methodology to psychological and neuroscientific evidence [5].

For 2D ground-based navigation we have specified several motor schemas and tested them successfully both in simulation and on our mobile robot George [2,3]. Those developed thus far include the following:

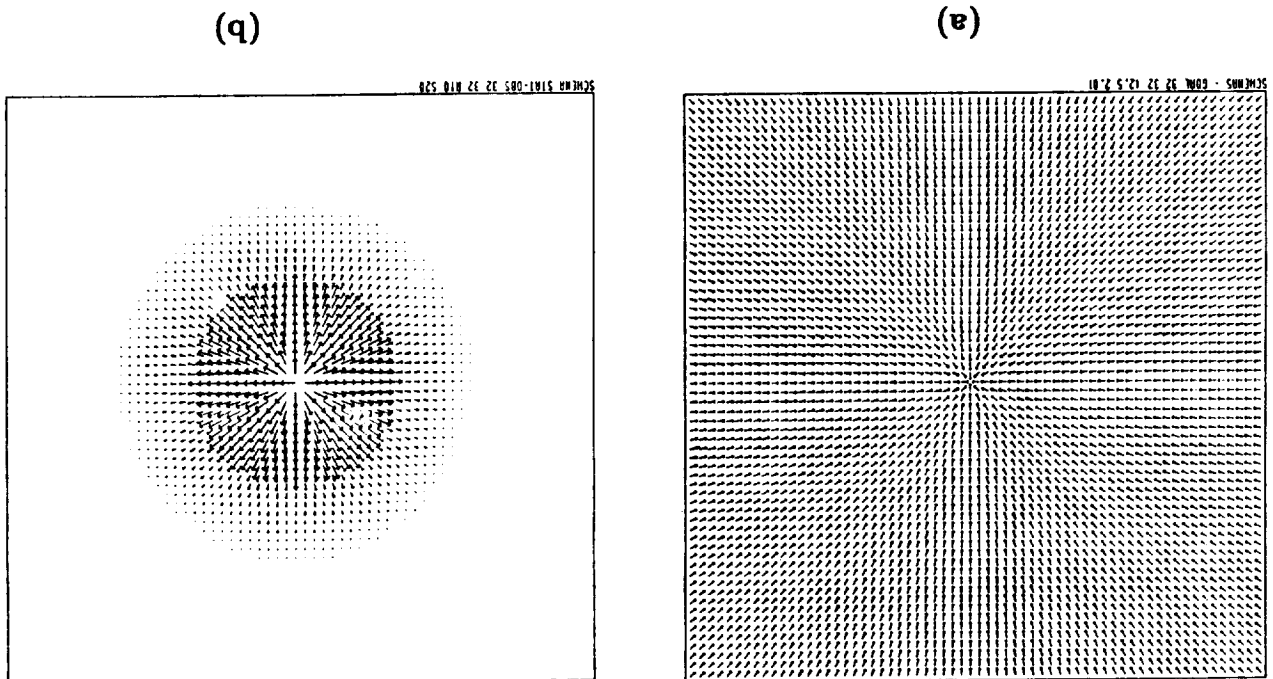
- **Move-ahead:** Move the robot in a general direction along the ground.
- **Move-to-goal:** Move the robot towards a recognized goal.
- **Avoid-static-obstacle:** Move the robot away from a detected obstacle.
- **Stay-on-path:** Keep the robot located on a hallway or road.

One must acknowledge the weaknesses of the potential fields methods along with its strengths. The possibility of local maxima, local minima, and cyclic behavior make any system that relies entirely upon this form of reflexive navigation prone to failure. We have previously reported a solution to the local maxima problem using a background noise process [1]. The other problems remain. For this reason AuRA incorporates a hierarchical planner which allows path and behavioral replanning at both the local and global levels when required. Navigational failure can be detected by observing that the velocity drops to zero while goal attainment has not been achieved (for local minima) or by exceeding a hard real-time deadline for goal completion (for cyclic behavior). In a teleoperated environment if cycle detection or deadlock due to local minima is detected the teleoperator could be informed allowing for human intervention and replanning.

Two of these 2D schemas are depicted in Figure 1. Although the entire vector field in these figures is illustrated for the reader's understanding, it should be noted that the robot computes only one vector for each of its active schemas based on its location relative to a detected environmental feature. No path planning is performed. Instead the robot reacts immediately to perceived sensor data as it navigates through the world.

- **Noise:** Add some randomness to the robot's motor behavior (useful for wandering and certain pitfalls in potential field navigation).
- **Docking:** Couple ballistic and controlled motion in a manner that allows a robot to safely approach a workstation.

**Figure 1: Representative Two Dimensional Motor schemas**  
 a) Move-to-goal.  
 b) Avoid-static-obstacle.



The advantages of schema-based reactive navigation are many. The ability to reflect uncertainty in perception, the simple mapping onto distributed processing systems, and the modular design facilitating incremental system growth are a few. These advantages also extend into our new work on three dimensional navigation described below.

### 3. Three dimensional schemas

Extending 2D schema-based navigation into three dimensions is a straightforward process. All of the schemas itemized above have been reformulated from 2D cartesian space to produce vectors in three dimensional space. Although the mathematics is a bit more complex and the computations a bit more costly than for the ground-based navigation, it is still a very low cost methodology for navigation.

Illustrations for two of the 3D motor schemas are presented in Figures 2-3. Both perceived environmental views and cross-sectional representations of the potential fields are presented. The schemas that are not shown in figures can be readily envisioned: the **avoid-static-obstacle** schema can be viewed as a repulsive sphere instead of a repulsive disk as shown in Figure 1b; the **move-to-goal** schema has vectors pointing from all directions towards the observed goal location; the **move-ahead** schema has identical vectors located at all locations in 3D space; and the **noise** schema has random vectors scattered in 3D space instead of 2D space. Our current formulations for the 3D motor schemas are presented below.

- **Avoid-static-obstacle:**

$$V_{magnitude} =$$

$$\begin{aligned} & 0 \text{ for } d > S \\ & \frac{S-d}{S-R} * G \text{ for } R < d \leq S \\ & \infty \text{ for } d \leq R \end{aligned}$$

where:

S = Sphere of influence (radial extent of force from the center of the obstacle)

R = Radius of obstacle

G = Gain

d = Distance of robot to center of obstacle

$V_{direction}$  = along a line from robot to center of obstacle moving away from obstacle

- **Stay-in-channel**

$$V_{magnitude} =$$

$$\begin{aligned} & P \text{ for } d > (W/2) \\ & \frac{d}{(W/2)} * G \text{ for } d \leq \frac{W}{2} \end{aligned}$$

where:

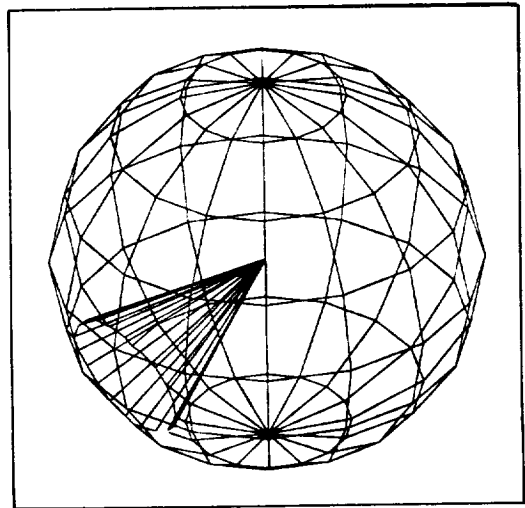
W = Width of channel

P = Off path gain

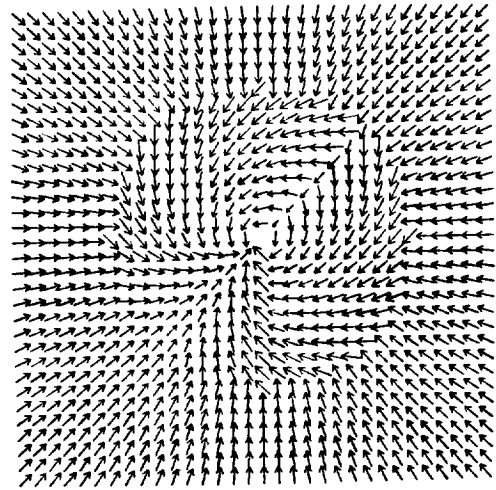
G = On path gain

d = Distance of robot to center of channel

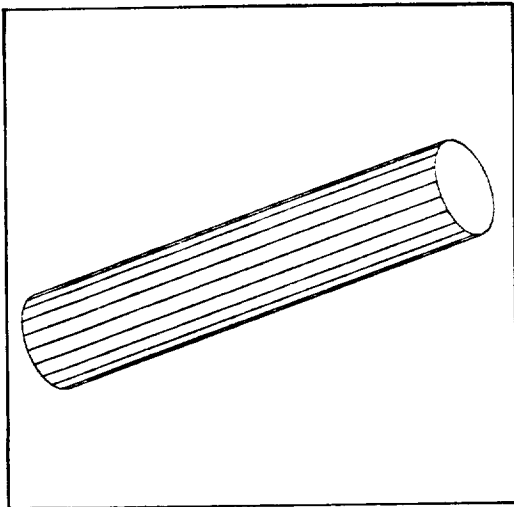
$V_{direction}$  = along a line from robot to center of channel heading toward centerline



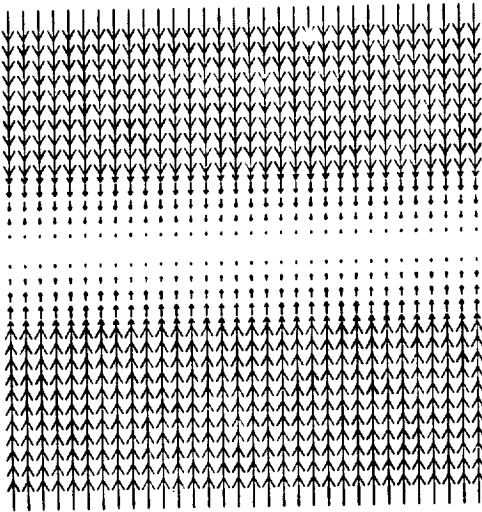
(2a)



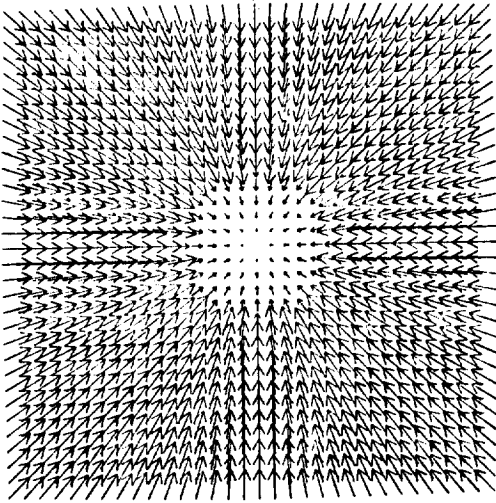
(2b)



(3a)



(3b)



(3c)

**Figure 2. Docking schema**  
a) Ballistic to controlled transition  
sphere and approach zone  
b) Cross-section of field sliced through  
center of approach zone.  
**Figure 3. Stay-in-channel - 3D analog**  
a) Channel representation  
b) Lengthwise cross-section of field.  
c) Perpendicular cross-section of field.

- **Move-ahead**  
 $V_{magnitude}$  = fixed gain value  
 $V_{direction}$  = in specified compass direction
- **Move-to-goal**  
 $V_{magnitude}$  = fixed gain value  
 $V_{direction}$  = in direction towards perceived goal
- **Noise**  
 $V_{magnitude}$  = fixed gain value  
 $V_{direction}$  = random direction
- **Docking**  
for ballistic component: same as **move-to-goal**.  
for controlled component (inside transition zone):  
for coercive zone (outside of approach zone): sum of a linearly decreasing tangential vector dependent on correctness of orientation and a constant attractive vector to the dock.  
for approach zone: sum of a constant tangential vector and linearly decreasing attractive vector dependent on distance from the dock.

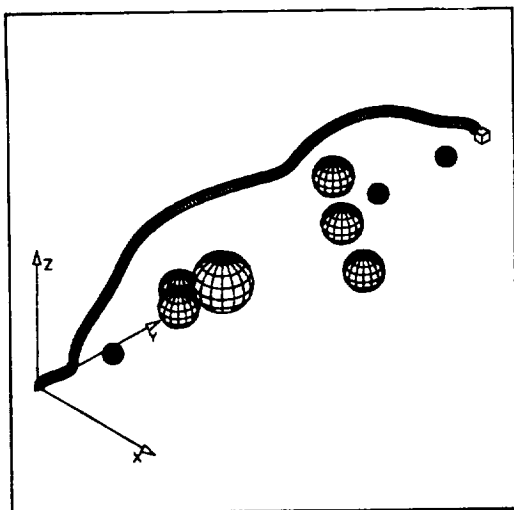
The actual control of a robot in the 3D domain is considerably more complex than the ground-based counterpart. This is a direct consequence of the increased number of degrees of freedom and the difficulty in controlling an object in free flight. Nonetheless the simulation studies presented in the next section show the success that can be attained if these engineering problems can be overcome.

## 4. Simulations

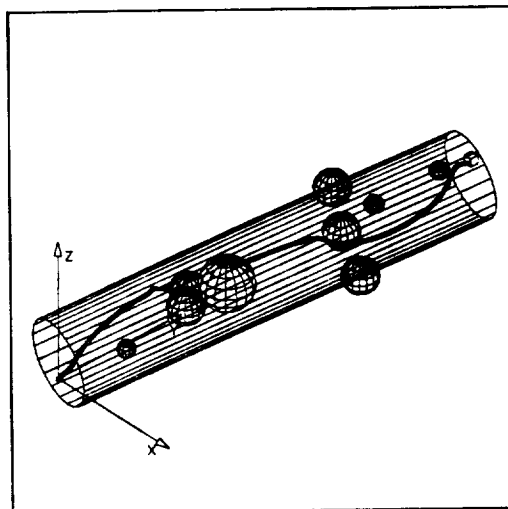
Several simulation runs are shown in Figure 4. These involve variations on a field of nine obstacles, a channel, and a goal or a dock. In each case, all of the behavioral goals are satisfied: there are no collisions with any of the obstacles, and where appropriate the robot remains within the channel and successfully migrates into the approach zone for the docking operation. Uncertainty in perception is built into this simulation run, with the robot's certainty of the presence of a particular obstacle decreasing with its distance from the obstacle. These examples clearly show that even in a highly cluttered world, reactive schema-based navigation can be successfully used to navigate a robot.

The first simulation run (Fig. 4a) shows a field containing nine obstacles. The robot starts at the origin and moves towards a goal on the other side of the obstacle field. One **Move-to-goal** schema and from zero to nine **avoid-static-obstacle** schemas are active at any one time (depending on the proximity of the robot to the obstacles). The robot is pushed away from the obstacle field while moving towards its goal, completing its mission successfully.

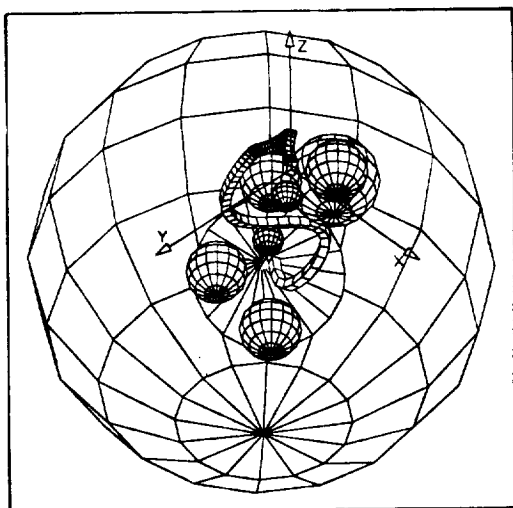
The same obstacle field and start and goal positions are present in the second simulation run (Fig. 4b). In this case, however, a **stay-in-channel** schema has been added. This forces the robot to negotiate the obstacles within the confines of the specified channel.



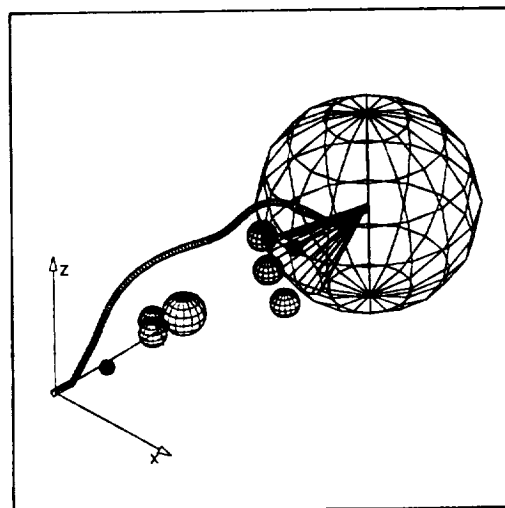
(a)



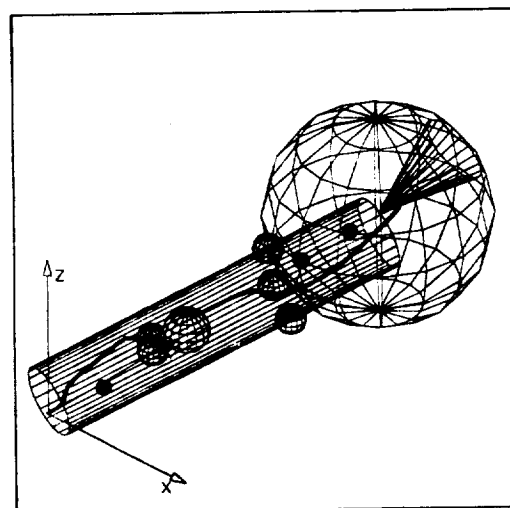
(b)



(c)



(d)



(e)

**Figure 4: Simulation runs**

Five different simulations of the route taken by a robot through a 3D course.

- a) 9 obstacles and a move-to-goal schema.
- b) Same as (a) with a stay-in-channel schema added.
- c) 9 obstacles, stay-in-channel and docking schemas.
- d) Same as (c) but with no stay-in-channel schema.
- e) Same as (c) but docking approach zone is in opposite direction.

The next simulation (Fig. 4c) contains the same configuration as Figure 4b but with the goal replaced by a docking schema. The channel is not illustrated in this figure for clarity but it is present nonetheless. This altered view from the origin looking towards the dock clearly shows the robot's path as it moves past the obstacles and safely into the approach zone of the docking schema.

Figure 4d shows the same simulation environment as that of Figure 4c but without the **stay-in-channel** schema. This path should also be compared to Figure 4a (the same environment but the **move-to-goal** has been replaced with the **docking** schema).

Finally, Figure 4e shows what occurs when the approach zone for the dock is on the opposite side of the channel. The robot enters into the controlled zone of the **docking** schema after successfully negotiating the obstacle course, and then is coerced to the opposite side before its final approach to the dock.

## 5. Summary and conclusions

We have demonstrated that schema-based navigation can be readily extended into three dimensional robot navigation domains. The advantages of this type of reactive control are many.

- Schemas are highly suitable for distributed processing.
- Their modular construction allows incremental development.
- They are responsive to environmental sensing.
- They can reflect uncertainty in perception.

We believe this work can be readily applied to both autonomous navigation and semi-autonomous teleoperation in space. By allowing the low-level obstacle avoidance and motor behaviors to be handled by reflexive sensing mechanisms, a teleoperator can be freed from the drudgery of the minute details of control and only needs to be concerned with the high-level intents of the robotic device. This approach can also cope with the large time lags in communication often found in space applications. The teleoperator can choose the behaviors that are relevant to a particular task and then let the robot strive, on its own, to satisfy the operator-specified goals. The fact that navigational snags can be detected through the use of hard real-time deadlines or the presence of unacceptably low velocities in the absence of goal attainment enables a teleoperator to be alarmed when these conditions occur. Autonomous operation, a major goal of our research, can also be developed by integrating planners that operate with a combination of *a priori* knowledge in addition to dynamically acquired world models.

Related work in progress includes the development of 3D path planning techniques based on the 2D navigational path planning strategies already in use in AURA [4]. The convex regions used in our "meadow map" for ground-based applications are being changed to convex volumes ("crystals") for path production in both undersea and aerospace applications. The A\* search algorithms will be modified accordingly for this domain. We are also developing new visual strategies that are applicable to the multiple perceptual needs of the docking operator. Work on the development of a complete planning and navigation system



capable of working in microgravity such as would be found in a space station environment is underway. The target robot would be capable of performing duties both in the interior and exterior of the spacecraft.

### Acknowledgments

The author would like to thank Warren Gardner for the production of the simulation graphics in this paper. This research is supported in part by the Computer Integrated Manufacturing Systems Program and the Material Handling Research Center at Georgia Tech.

### REFERENCES

- [1] Arkin R., (1987). "Motor Schema Based Navigation for a Mobile Robot: An Approach to Programming by Behavior", *Proc. IEEE International Conference on Robotics and Automation*, Raleigh, N.C., pp. 264-271.
- [2] Arkin, R., (1987). "Towards Cosmopolitan Robots: Intelligent Navigation of a Mobile Robot in Extended Man-made Environments", *Ph.D. Dissertation, COINS Technical Report 87-80*, Department of Computer and Information Science, University of Massachusetts.
- [3] Arkin, R., (1988). "Intelligent Mobile Robots in the Workplace: Leaving the Guide Behind", *Proceedings of The First International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems*, pp. 553-561.
- [4] Arkin, R., (1989). "Navigational Path Planning for a Vision-based Mobile Robot", To appear in *Robotica*.
- [5] Arkin, R., (1988). "Neuroscience in motion: The Application of Schema Theory to Mobile Robotics", chapter to appear in *Visuomotor Coordination: Amphibians, Comparisons, Models, and Robots*, eds. J.-P. Ewert and M. Arbib. New York: Plenum Press.
- [6] Arkin, R., Riseman, E. and Hanson, A., (1987). "Visual Strategies for Mobile Robot Navigation", *Proceedings of the IEEE Computer Society Workshop on Computer Vision*, Miami Beach, Florida, pp. 176-181.
- [7] Brooks, R., (1986). "A Robust Layered Control System for a Mobile Robot", *IEEE Jour. of Robotics and Auto.*, Vol. RA-2, No. 1, pp. 14-23.
- [8] Kadonoff, M., Benayad-Cherif, F., Franklin, A., Maddox, J., Muller, L., Sert, B. and Moravec, H., (1986). "Arbitration of Multiple Control Strategies for Mobile Robots", *Mobile Robots - SPIE proc. Vol. 727*.
- [9] Khatib, O. (1985), "Real-time Obstacle Avoidance for Manipulators and Mobile Robots", *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 500-505, St. Louis.
- [10] Krogh, B. (1984). "A Generalized Potential Field Approach to Obstacle Avoidance Control", *SME - RI Technical Paper MS84-484*.
- [11] Krogh, B. and Thorpe, C., (1986). "Integrated Path Planning and Dynamic Steering Control for Autonomous Vehicles", *IEEE Conf. on Robotics and Auto.*, pp. 1664-1669.
- [12] Payton, D., (1986). "An Architecture for Reflexive Autonomous Vehicle Control", *IEEE Conf. on Robotics and Auto.*, pp. 1838-1845.

